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ISOTHERMAL FLOW OF GAS IN A CYLINDRICAL PIPE

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/Figures are appended./

/NOTE: This report studies an important phenomenon of reversibility, of interest in heat exchangers and jet engines./

Equations of Isothermal Flow

Let us describe the unidimensional motion of gas in a pipe, when heat exchange and friction are present, thus:

$$(M^2 - 1)\frac{w}{g}dw = - M^2(kdL_r + \frac{k-1}{A} dQ_e) \tag{1}$$

where $dQ_e = qdx$ is the element of external heat and $dl_r = dx \cdot \lambda w^2/2gD$ is the element of work done against friction (resistance), per kilogram of gas in the path dx; also $M^2 = w^2/a^2$. (Q_e = external heat.)

Replacing wdw/g in (1) by its value from the energy equation $dQ_e = c_p dT + Awdw/g$, we find:

$$(M^2 - 1)\, c_p dT = kM^2 dQ_r - (1 - kM^2)dQ_e \tag{2}$$

It follows from (2) that the condition governing the existance of isothermal flow ($dT = 0$) in a pipe is:

$$dQ_e = kM^2 dQ_r/(1 - kM^2) \quad (Q_r \text{ is the heat of friction}). \tag{3}$$

It also follows that isothermal flow in a pipe cannot be realized without friction.

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Placing the value of dQ_e from (3) into (1), we obtain:

$$(1 - kM^2)\, wdw/g = kM^2 dL_r. \tag{4}$$

Finally, replacing wdw/g in (4) by its value from Bernoulli's equation $wdw/g + vdp + dL_r = 0$, we find:

$$(1 - kM^2)\, vdp = - dL_r \cdot w^2/g \tag{5}$$

Physical Peculiarities of a Gas Limit State in Isothermal Flow

From equations (3), (4), (5) it follows that isothermal flow is a limiting state and that its singular (critical) point corresponds to the number $M^* = 1/\sqrt{k}$; for $k = 1.4$, $M^* \approx 0.845$,

Actually, since $dL_r/dx = \lambda w^2/2gD$ is always essentially positive, we have, for $M^* = 1/\sqrt{k}$, $dp^*/dx = dw^*/dx = dQ_e^*/dx = q = dM^*/dx = ds^*/dx = \infty$, since $ds = dQ/T = (dQ_e + dQ_r)/T = dQ_r/T(1 - kM^2)$.

Thus, a continuous transition through $M = 1/\sqrt{k}$ in isothermal flow is impossible (see Figure 1).

The physical meaning of the limiting state of isothermal flow consists, consequently, of this: to preserve T = constant at the singular point the intensity of heat supply ($q = dQ_e/dx$) increases without limit.

Let us investigate the frictional process at the singular point. We find from (4) $dL/dM = (1 - kM^2)RT/M$; hence, $dL_r^*/dM = 0$ ($M = 1/\sqrt{k}$). In addition, $dL_r^*/dx = \lambda RT/2D \neq 0$.

From $dL_r^*/dx \neq 0$ and $dL_r^*/dM = 0$ we obtain another important peculiarity of the limiting state of isothermal flow: at the singular point the frictional process proceeds on the reverse isotherm, since all the heat of friction is converted reversibly [literally "back"] into kinetic energy of flow. But just as the presence of friction accounts for the presence of isothermal (irreversible) flow, so the reversibility of the process in the limiting state excludes the possibility of T = const. flow in a cylindrical pipe.

It also follows from equations (3), (4), (5) that when external heat is supplied ($dQ_e > 0$) isothermal flow can be realized only in the region $0 < M < M^*$ ($= 1/\sqrt{k}$).

When heat is carried off ($dQ_v < 0$) isothermal flow is possible only in the region $M^* < M < \infty$.

Relation Between Gas Parameters and Dimensionless Length of Pipe

The gas parameters in isothermal flow are related by the following ratios:

$$w_2/w_1 = v_2/v_1 = p_1/p_2 = M_2/M_1 \tag{6}$$

The relation between the dimensionless length of the pipe and the number M is given by the expression:

$$\lambda x/D = 2 \ln M_1/M_2 - (1/k) \cdot (M_2^{-2} - M_1^{-2}), \tag{7}$$

which is found from the integration (3) of Bernoulli's equation (by setting λ = constant): $wdw/g + vdp + \lambda w^2 dx/2gD = 0$. (Note: The assumption that λ is independent of Re is sufficiently accurate for large values of the Re numbers ($> 10^5$), for both smooth and rough pipes. Thus, it follows from Nikuradze's well-known formula $\lambda = 0.0032 + 0.221/Re^{0.237}$ that λ decreases 24% when Re increases from 10^7 to 10^8. Numerical investigations have not revealed any influence of M upon λ.)

Figure 2 shows the influence of initial M_1 on the limiting value of $\lambda x^*/D$, corresponding to $M^* = 1/\sqrt{k}$. Employing the ratios (6) and equation (7) one can find the functions $M(x)$, $w(x)$, $p(x)$, $\gamma(x)$.

Determination of Heat Supplied to a Gas in Isothermal Flow

External heat: $Q_e = A(w_2^2 - w_1^2)/2g = \frac{1}{2} AkRT(M_2^2 - M_1^2)$ (8)

Total heat: $Q_t = T\Delta S = ART \cdot \ln M_2/M_1$ (9)

Heat of friction: $Q_r = Q_t - Q_e = ART[\ln M_2/M_1 - \frac{1}{2}k(M_2^2 - M_1^2)]$ (10)

Figure 3 shows the influence of the number M upon Q_e, Q_t, Q_r and also upon the function

$$dQ_e/dQ_r = 2q/\lambda AkRT - kM^2/(1 - kM^2) \tag{11}$$

which is proportional to the intensity of heat supply.

Variation of the Temperature of the Pipe's Wall With the Number M

Let the external heat (Q_e) required for maintenance of constant temperature be supplied through the wall of the channel. Then, on the basis of the hydrodynamic theory of heat exchange (2), we have:

$$dQ_e = \frac{\lambda c p}{2D}(T_W - T_o)dx = \frac{1}{2}\lambda c_p T(1+\frac{k-1}{2}M^2)(\Theta - 1)\frac{dx}{D} \tag{12}$$

where $\Theta = T_w/T_o$ is the dimensionless temperature of the wall, T_w is the temperature of the wall, and $T_o = T(1+\frac{k-1}{2}M^2)$ is the temperature of the completely stopped flow in the boundary layer.

Setting in (3) the value of dQ_e from (8) and dL_r, we find after a transformation:

$$\Theta = T_w/T_o = 1 + kM^4(1 - kM^2)^{-1} \cdot (1 - \frac{k-1}{2}M^2)^{-1}; \tag{13}$$

$$T_w/T \quad (1+\frac{k-1}{2}M^2 + \frac{kM^4}{1-kM^2}); \tag{13^1}$$

when $M = 0$, then $\Theta = 1$ and $T_w/T = 1$;

when $M = M^* = 1/\sqrt{k}$, then $\Theta = \infty$ and $T_w/T = \infty$.

Consequently, to the variation of M in the limits $M^* > M > 0$ corresponds the variation of Θ and T_w/T in the limits $\infty > \Theta > 1$ and $\infty > T_w/T > 1$ (See Figure 4).

Formulas (7) and (13) permit one to determine the variation of the wall's temperature along the pipe.

Conslusions

1. The limiting states in gas flows with heat exchange and in the presence of friction, which are connected with the transition through the speed of sound, are well known and studied: I. I. Novikov [1] has shown that these flows (except isentropic flow) are not polytropic (n = constant $\neq k$), since at the singular point the process necessarily takes place isentropically along the reversible adiabatic curve ($n = k$).

2. From the above, however, it follows that there exist even other classes of limiting flows. To them, for example, belongs isothermal flow with friction ($n = 1$), for which the limiting state is determined by the transition through $M = 1/\sqrt{k}$.

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3. In the limiting state the process of flow in a real gas proceeds reversibly [1, 2]; this means that at the singular point the heat of friction is converted reversibly to the kinetic energy of flow.

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2. S. A. Khristianovich, Applied Gas Dynamics (Prikladnaya Gazovaya Dinamika) 1948.

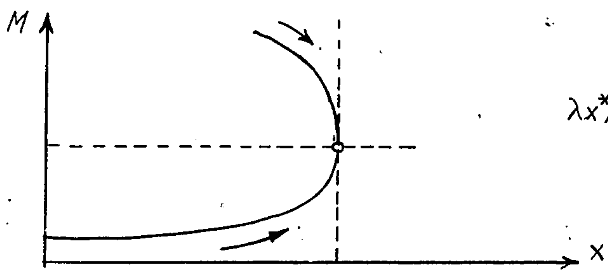

Figure 1. Variation of the Number M Along a Pipe During Isothermal Flow

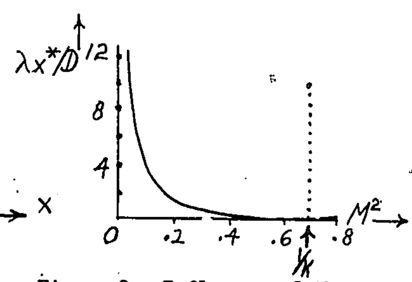

Figure 2. Influence of the Number M_1 on the Parameter $\lambda x^*/D (M_2^2 = 1/k)$

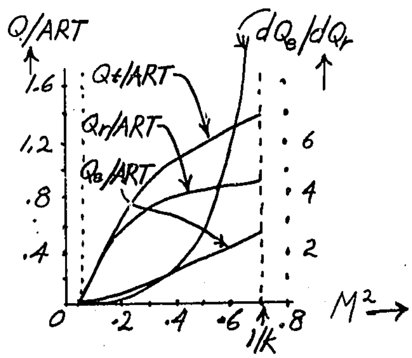

Figure 3. Influence of the Number M on the Heat Supplied to a Gas in Isothermal Flow ($M_1^2 = 0.05$)

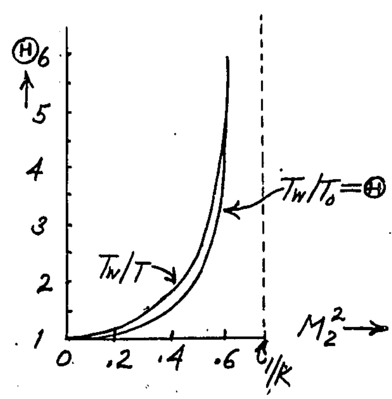

Figure 4. Influence of the Number M on the Dimensionless Temperature of the Wall During Isothermal Gas Flow

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